Radiological Modelling Software for Underground Uranium Mines

Brian Bjorndal[1] and Reza Moridi[2]
[1]Canadian Institute for Radiation Safety (CAIRS), Saskatoon, Saskatchewan, Canada;
[2]Canadian Institute for Radiation Safety (CAIRS), Toronto, Ontario, Canada

ABSTRACT

The Canadian Institute for Radiation Safety (CAIRS) has been developed computer simulation software for modelling radiological parameters in underground uranium mines. The computer program, called 3d RAD, allows radiation protection professionals and mine ventilation engineers to quickly simulate radon and radon progeny activity concentrations and potential alpha energy concentrations in complex mine networks. The simulation component of 3d RAD, called RSOLVER, is an adaptation of an existing modelling program called VENTRAD, originally developed at Queen's University, Ontario. Based on user defined radiation source terms and network physical properties, radiological parameters in the network are calculated iteratively by solving Bateman's Equations in differential form. The 3d RAD user interface was designed in cooperation with the Canada Centre for Mineral and Energy Technology (CANMET)to improve program functionality and to make 3d RAD compatible with the CANMET ventilation simulation program, 3d CANVENT. The 3d RAD program was tested using physical data collected in Canadian uranium mines. 3d RAD predictions were found to agree well with theoretical calculations and simulation results obtained from other modelling programs such as VENTRAD. Agreement with measured radon and radon progeny levels was also observed. However, the level of agreement was found to depend heavily on the precision of source term data, and on the measurement protocol used to collect radon and radon progeny levels for comparison with the simulation results. The design and development of 3d RAD was carried out under contract with the Saskatchewan government.

KEYWORDS

Radon, Radon Progeny, Modelling, Radiation Software, Ventilation, 3d Rad, and Underground Mine.

INTRODUCTION

It is well known that the airborne progeny of naturally occurring radon gas (^{222}Rn) can present a serious radiation hazard. As radon and its short lived progeny are decay products of uranium, health risks associated with exposure to radon progeny is particularly evident for individuals working in the uranium mining industry.

Radon and radon progeny exposures in underground uranium mines are minimized through proper design, engineering control and the establishment of an effective radiation protection program. To meet these ends, radiological modelling is often utilized to predict radiation levels. The information provided is used in the design of ventilation systems, appropriate engineering controls and mining processes.

The Canadian Institute for Radiation Safety (CAIRS) has developed a computer simulation program for modelling radiological parameters in underground uranium mines. The program was developed as part of a contract with the Saskatchewan Government to improve radiological modelling techniques for underground uranium mines.

The computer program, called 3D Rad, allows radiation protection professionals and ventilation engineers to quickly simulate radon and radon progeny activity concentrations and potential alpha energy concentrations (PAEC) in complex mine networks.

The simulation component of 3D Rad, called Rsolver, is an adaption of an existing modelling program called VENTRAD which was originally developed at Queen's University, Ontario.

RADON PROGENY MODELS

Over the past several decades, a number of models predicting the levels of radon and radon progeny in underground uranium mines have been developed (Evans, 1969; SENES, 1984; Bigu, 1982). Some of these models include the Evans Mine Model (EMM) and the Isolated Mine Model (IMM) which are essentially strict applications of radioactive decay of a point source using Bateman's Equations. Other models such as the Mine-Tunnel with Ventilation (MTMV), the Thomas-Epps Mine Model (TEMM) and the Modified Mine-Tunnel Model with Ventilation (MMTMV) are more complex in that they attempt to incorporate more realistic parameters such as ventilation, radon flux from mine walls, the age differences of radioactive gas in the mine environment and radiation loss mechanisms. In general however, these mine models show only a partial agreement when compared to experimental data and are indistinguishable for practical application on the basis of the experimental evidence so far collected (Bigu, 1985). The reason for the lack of agreement has been attributed to the unrealistic assumptions on which the models are based. This is compounded by the gross over-simplification of the quite complex dynamic situation encountered in an actual mining environment. Quite often, simpler and less realistic models produce results that are in better agreement with experimental data.

CAIRS MINE MODEL

Introduction

In light of the fact that more complex models do not necessarily yield improved simulation results, the CAIRS mine modelling design was based on the simple physical principles of radioactive decay. Radiation removal mechanisms such as plate-out and gravitational settling were not incorporated into the model design primarily because of the inherent difficulties associated with quantifying the magnitude of such removal mechanisms.

Theoretical Model

In the CAIRS model, radon and radon progeny concentrations were determined by utilizing a set of differential equations known as Bateman's Equations. These equations have the general form:

$$\frac{dN_i}{dt} = N_{i-1}\lambda_{i-1} - N_i\lambda_i \tag{1}$$

where N represents the number of atoms, λ the decay constant and $N_i\lambda_i$ the activity I_i of the i^{th} radon progeny. The corresponding activity of the $(i-1)^{th}$ radionuclide is given by $N_{i-1}\lambda_{i-1}$ and describes the rate of supply of the i^{th} radon progeny. The differential Equation (1) describes the rate of change of the number of i^{th} radon progeny atoms given a supply term $N_{i-1}\lambda_{i-1}$ and a decay term $N_i\lambda_i$.

In radon progeny modelling, the primary decay products of interest are the short lived alpha emitting radionuclides ^{218}Po (RaA), ^{214}Pb (RaB) and ^{214}Bi (RaC). As the half life of ^{214}Po (RaC') is very short (1.64×10^{-4} s^{-1}), the activity of RaC' can be taken to be equal to the activity of its parent RaC and thus ignored in the calculations.

The rate of change of activity of the i^{th} radon progeny can be derived from Equation (1)

$$\frac{dI_i}{dt} = \lambda_i(I_{i-1} - I_i) \tag{2}$$

noting that the activity is defined as $I = \lambda N$.
Rewriting Equation (2), one obtains the expression

$$dI_i = \lambda_i dt(I_{i-1} - I_i) \tag{3}$$

which describes the differential change in activity of the i^{th} radon progeny given the activity of the $(i-1)^{th}$ radon progeny.

The differential equation governing the rate of change of radon has the form

$$\frac{dN}{dt} = S - N\lambda \tag{4}$$

where N refers to the number of radon atoms. The parameters S and λ denote the radon source term and the decay constant of radon. The source term S, refers to the radon activity generated from mine walls.

To determine the activity concentrations R_i of each of the radionuclides in the drifts of an underground mine, one can use an expression similar to Equation (3)

$$R_i = R_{i0} + \Delta R_i(t) \tag{5}$$

where R_{i0} denotes the initial activity concentration and ΔR_i the activity concentration increment in the time interval t.

If the time interval is very small, the term $\Delta R_i(t)$ can be replaced by the differential change in activity concentration dR_i. By using this formulation together with Equations (3) and (4), one can obtain explicit expressions for the differential change in activity concentrations for radon and radon progeny. The general equation for the growth of radon has the form

$$R = R_0 + dt(R_s - \lambda R_0) \tag{6}$$

where the radon source term activity concentration per unit time, R_s is equal to λS.

Similar expressions can be derived for the growth of radon progeny

$$R_i = R_{i0} + \lambda_i dt(R_i - R_{i0}) \tag{7}$$

If the time differential dt is chosen to be sufficiently small (of the order of seconds), then Equations (6) and (7) become approximately linear in time.

A typical underground mining tunnel is characterized by a number of quantities including its length L, cross sectional area, A and ventilation flow, Q. By splitting the length of the airway L into small differential segments dx, one can determine the increment of time required for the air to flow across dx

$$dt = \frac{A}{Q} dx \tag{8}$$

Similarly, one can obtain a practical expression for the radon activity concentration per unit time, R_S in terms of mine physical parameters. As radon source terms are typically expressed in terms of a flux or exhalation (Bq/m^2/s) from tunnel surfaces, the term R_S can be rewritten as

$$R_S = \frac{E\ A_s}{L\ A} \tag{9}$$

where E denotes the radon flux in units of Bq/m^2/s and L the length of the tunnel. The variables A_s and A refer to the tunnel surface area and cross sectional area respectively.

With the preceding theoretic development, a set of activity concentration equations for radon and radon progeny can be derived in terms of physical and radiological mine parameters.

Radon:

$$R = R_0 + \left(\frac{E\ A_s}{L\ A} - \lambda R_0\right)\frac{A}{Q}dx \tag{10}$$

Radon Progeny:

$$R_i = R_{i0} + \lambda_i (R_{i-1} - R_{i0})\frac{A}{Q}dx \tag{11}$$

The differential length element dx, is chosen to be sufficiently small such that the activity concentrations given are linear in time.

To examine how the activity expression can be applied in a typical mine drift, consider a tunnel of length L, cross sectional area A and ventilation flow Q (see Figure 1).

The length of the tunnel is divided up into differential segments dx. Radon and radon progeny entering a segment dx are incremented by radon source terms, ΔR within dx. The resulting radon and radon progeny exiting the segment dx become the initial levels for the adjacent segment dx. This iterative process is continued through each branch until all branches of the network have been solved.

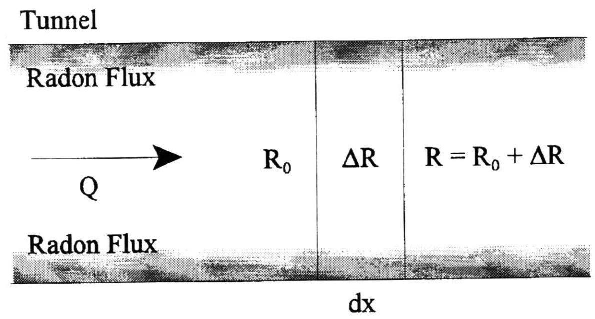

Figure 1. Illustration of radon progeny growth in a mine tunnel.

Potential Alpha Energy Concentrations

Potential alpha energy concentrations (PAEC) are calculated from the modelled radon progeny activity concentrations using the expression

$$PAEC[WL] = \frac{265 R_{RaA}(13.68) + (2320 R_{RaB} + 1706 R_{RaC})7.68}{1.3 \times 10^{8}} \tag{12}$$

The terms R_{RaA}, R_{RaB} and R_{RaC} refer to the RaA, RaB and RaC activity concentrations respectively.

Radon Point Sources

Often in an underground mine, there exists isolated point sources of radon in addition to radon flux from tunnel walls. Examples of such point sources include water inflows, rock fractures or concentrated uranium ore bodies in a drift. The CAIRS modelling software is designed to include such point sources when they occur in a mine. During simulation calculations, radon point sources specified in a differential segment, dx are simply added to the total radon concentration at that location and used in subsequent calculations for the growth and decay of radon and radon progeny.

When point sources occur, Equation (10) takes the form

$$R = R_0 + \frac{R_P}{Q} + \left(R_S - \lambda\left(R_0 + \frac{R_P}{Q}\right)\right)\frac{A}{Q}dx \tag{13}$$

where the term R_P denotes the radon point source in units of Bq/s.

3D Rad Software

Introduction

The radiological modelling program 3D Rad is a Microsoft Windows 95® based program designed to simulate radon and radon progeny levels in underground mine networks. Based on user defined radiation source terms and network physical properties, radiological parameters are calculated interatively by solving Bateman's Equations in differential form.

3D Rad is an upgrade of a program called MINE which was also developed by CAIRS under contract with the Saskatchewan Government (CAIRS, 1998).

The primary difference between the programs 3D Rad and MINE is with their user interfaces. MINE is a DOS based program while 3D Rad is a Windows 95® based program. Radon and radon progeny simulation calculations are performed using the same techniques presented thus far. The calculation module within 3D Rad is called Rsolver.

The simulation module, Rsolver is an adaptation of an earlier program called VENTRAD originally developed at Queen's University (SENES, 1984). VENTRAD has been widely used in Canada for radiological modelling in uranium mines.

Unlike 3D Rad, the program VENTRAD simulates radon concentrations and PAEC using analytic time dependent equations. VENTRAD does not provide radon progeny activity concentrations.

The Windows 95® interface for 3D Rad was designed by the Canada Centre for Mineral and Energy Technology (CANMET) in cooperation with CAIRS and the Saskatchewan Government (CAIRS, 1998).

By design, the 3D Rad is compatible with the CANMET ventilation simulation programs 3D CANVENT (CAIRS, 1998). Mine networks and ventilation results generated within 3D CANVENT can be imported directly into 3D Rad for radon and radon progeny modelling.

Software Description

The 3D Rad software is comprised of two modules: a user interface which allows the user to create mine networks and enter physical and radiological parameters, and a computation module which carries out the simulation calculations.

The 3D Rad application workspace is shown in Figure 2. A fictitious mine network is displayed in the viewing windows of the work space.

Software commands are accessed via the menu bar located at the top of the 3D Rad workspace.

The 3D Rad work space contains four viewing windows which display the mine network in Cartesian Coordinates. Three of the viewing windows display the network as viewed along each axis (x, y and z). The fourth viewing window displays the network in three dimensions. All views can be magnified or reduced in size as well as rotated.

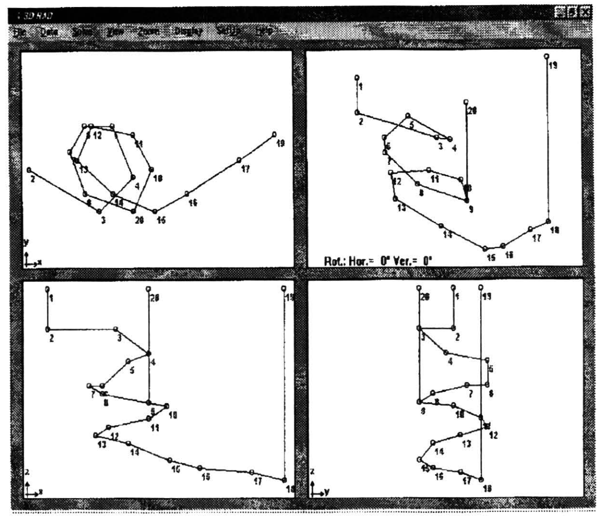

Figure 2. 3D Rad desktop workspace.

Creating Mine Network

Modelling with 3D Rad is a three step process: creating the mine network, adding physical and radiological data and executing the simulation module.

A mine layout is created in 3D Rad by first defining branch (drift) "junctions". Junctions are the endpoints of each branch in the network. A junction is defined by specifying its coordinates and giving the junction a unique identification number. Junctions are added using the Add/ Edit Junctions Data controls shown in Figure 3.

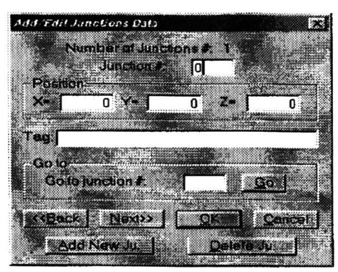

Figure 3. Add/Edit junctions data dialogue box.

By design, junction coordinates are used only to provide a visual representation of the mine network. Modelling can be conducted without creating a visual representation of the mine network. The coordinates are not used to determine drift lengths. This eliminates the necessity of acquiring detailed coordinates of the network layout to be modelled.

Adding Physical and Radiological Data

Network physical characteristics, ventilation data and radon source terms are entered using the Add/Edit Branch Data controls shown in Figure 4.

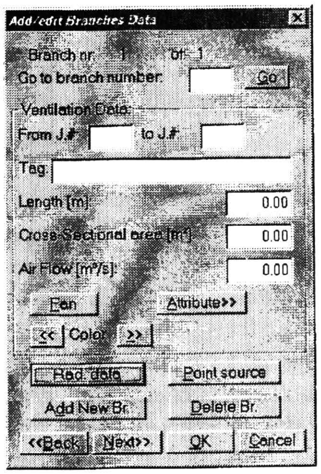

Figure 4. Add/Edit branch data dialogue box.

Radon source terms are added either in the form of an overall branch radon flux, radon point sources or a combination there of. Up to five radon point sources and their locations can be added in any one branch.

Branch attributes such as air flow direction, junctions numbers and radon point sources can be displayed in the 3D Rad workspace viewing windows (see Figure 5). The arrows represent the direction of the air flow in each branch.

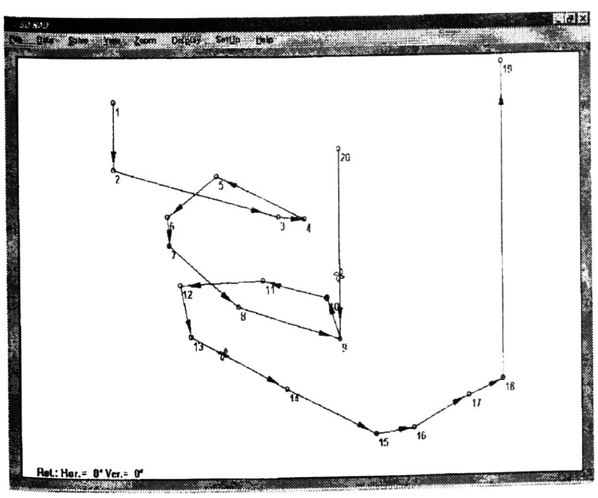

Figure 5. View showing 3D Display of a Mine Network with Branch Attributes.

Running Simulations

Once all branch data has been entered for the network, modelling can proceed. Using the information provided by the user, radon and radon progeny concentrations and PAEC are calculated throughout the network using the simulation module Rsolver. The results of the simulation can be displayed directly in the viewing windows or viewed through a results dialogue box shown in Figure 6.

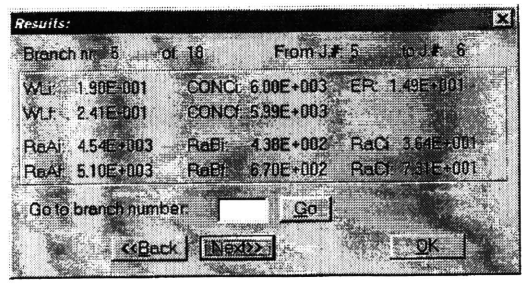

Figure 6. Results dialogue box.

Simulation results are computed for each branch junction of the network. Results with subscripts i refer to the beginning junction of a branch and the subscript f refers to the end junction of the branch. Radon and radon progeny concentrations are given in units of Bq/m^3. PAEC levels are expressed in units of Working Levels (1 WL = 2.08×10^{-5} J/m^3).

3D Rad does not balance air flows in the network during the simulation. The user must balance the network prior to running the simulation either manually or using another program such as 3D CANVENT (CANMET, 1997).

Data Output

Mine network physical parameters and simulation results can be exported directly to a spreadsheet or text file format for printing or further examination.

Any or all of the mine layout views can be printed directly within 3D Rad.

Program Testing

During the development of 3D Rad, the program was tested against VENTRAD in fictitious mine networks under varying scenarios. 3D Rad was found to generate radon concentrations and PAEC which were consistent with VENTRAD.

The performance of 3D Rad was also examined in field modelling tests at working underground uranium mines in Canada. Following are results of one such modelling field test.

Modelling field tests of 3D Rad were conducted using data collected in a small section of a Canadian underground uranium mine (CAIRS, 1998). The section of the mine used in the field tests is shown in Figure 7.

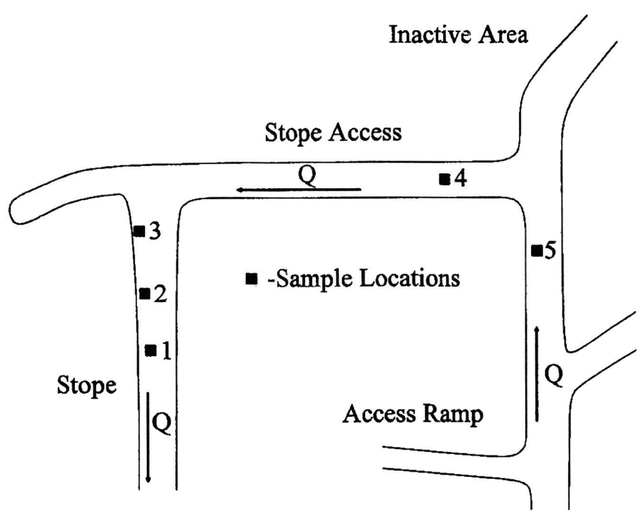

Figure 7. Mine Test Area.

The results were compared with physical grab sample measurements collected at the mine using the Thomas Method (CAIRS, 1998; Thomas, 1969). 3D Rad simulation results and measured radiation levels are shown in Figures 8 through 10.

As can be seen in Figures 9 and 10, radon concentration and PAEC predictions by 3D Rad agree well with observed levels at all sample locations.

Some notable variations were observed with respect to the simulated and measured radon progeny concentrations. It is readily apparent from Figure 8 that the age of air as predicted with 3D Rad is younger than the measured age of air. Simulated RaA concentrations were higher than observed concentrations while simulated RaC concentrations were lower than observed concentrations. This indicates a shorter ingrowth time of the radon progeny as predicted by 3D Rad.

These results were not surprising as 3D Rad assumes smooth drift surfaces and a uniform air flow through each drift of the mine. The presence of nonuniform drift surfaces, remucks, bulk heads, sumps and mining equipment, etc. can result in areas of perturbed or reduced air flow, and in some instances pockets of dead air space. All of the aforementioned factors can contribute to a measured longer age of air.

It was also observed that the success of radiological modelling was highly sensitive to the quality of the radon source terms used. Inaccurate estimates or measurements of radon source terms invariably leads to unreliable simulation results.

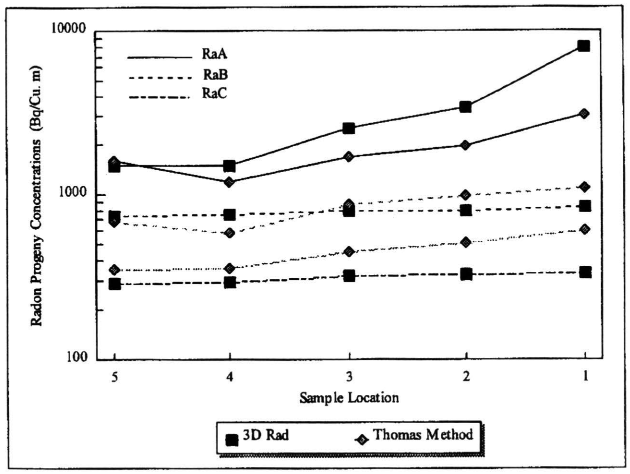

Figure 8. Radon progeny concentration results at the mine test area.

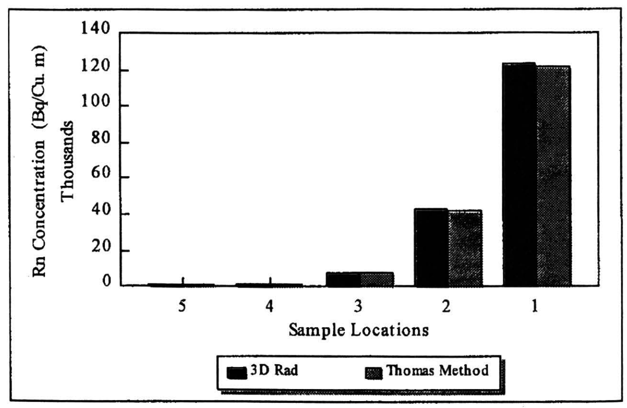

Figure 9. Radon concentration results at the mine test area.

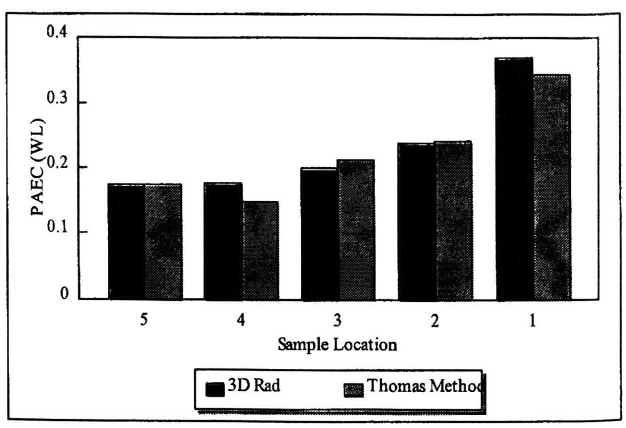

Figure 10. PAEC results at the mine test area.

CONCLUSION

The CAIRS radiological modelling program 3D Rad is designed to simulate radon and radon progeny concentrations and PAEC in underground mine networks.

3D Rad utilizes the basic principles of radioactive decay to predict radiation levels in mine networks by solving Bateman's Equations in differential form.

The program has direct applications in ventilation design of mine networks and the maintenance of effective radiation protection programs.

Testing of the 3D Rad was conducted under numerous scenarios using both fictitious and actual working underground uranium mines. Simulation results obtained from modelling were found to be consistent with observed values when representative radon source terms were used.

However, as with all radiological modelling software, 3D Rad is sensitive to the accuracy of the input parameters used in the simulation. In order to conduct reliable simulations, quality input data is required, particularly ventilation data and radon source terms.

3D Rad provides a user friendly Windows® interface allowing for quick and efficient modelling of complex mine networks. 3D Rad provides a functional, user friendly environment in which to perform simulations. As 3D Rad is compatible with the CANMET program 3D CANVENT, radiological consequences of ventilation designs can be quickly examined.

From a computing standpoint, 3D Rad offers a significant advancement in radiological modelling for underground uranium mines.

REFERENCES

Bigu, J., "Theoretical Models For Determining ^{222}Rn and ^{220}Rn Progeny Levels in Canadian Underground Uranium Mines - A Comparison With Experimental Data," Health Physics, Vol 48, No. 4, 1985.

CAIRS, "Radiological Modelling for Underground Uranium Mines," A report prepared for the Saskatchewan Government, Canadian Institute for Radiation Safety, June, 1998.

CANMET, Ventilation Simulation Software, 3D CANVENT, Canada Centre for Mineral and Energy Technology, (CANMET), 1997.

Evans, R.D., "Engineers' Guide to the Elementary Behaviour of Radon Daughters," Health Physics Vol. 17. 1969.

SENES Consultants Limited, "Computer Modelling of an Underground Mine Ventilation System," A research report for the Atomic energy Control Board, INFO-0145, Ottawa, Canada. 1984.

Thomas, J.W., "Measurement of Radon Daughters in Air," Health Physics, Vol. 23, 1972.